Highly conductive p^{++}-AlGaAs/n^{++}-GaInP tunnel junctions for operation up to 15,000 suns in concentrator solar cells

In the last few decades there has been great interest in III-V multi-junction solar cells (MJSC) for concentrator applications due to their promise to significantly reduce the cost of electricity.

Being formed by series connection of several solar cells with different bandgaps, a key role in a MJSC structure is played by the tunnel junctions (TJ) aimed to implement such series connection. Essentially, tunnel junctions (tunnel diodes or Esaki diodes) are thin, heavily doped p–n junctions where quantum tunneling plays a key role as a conduction mechanism. Such devices were discovered by Nobel laureate Leo Esaki at the end of 1950.

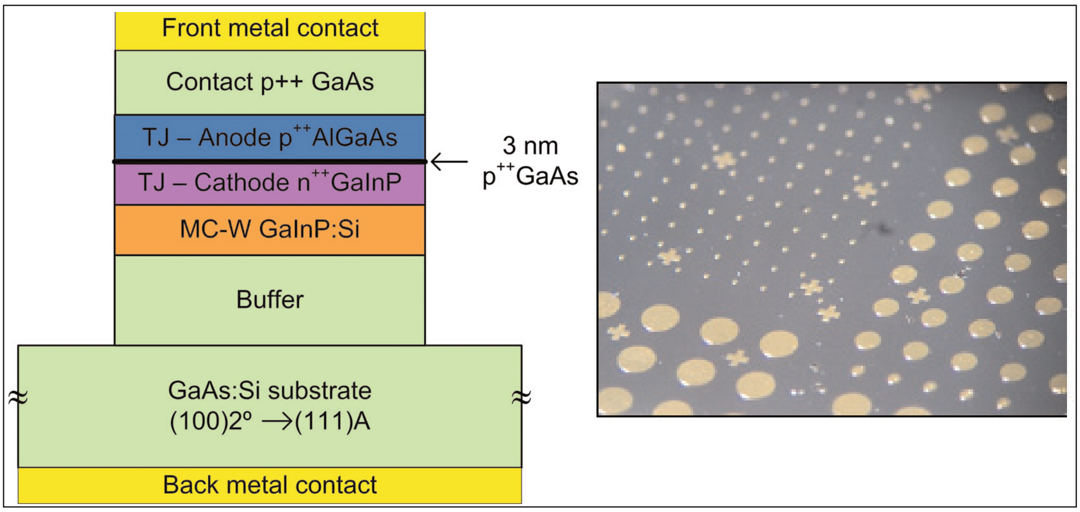

Figure 1 (left) Semiconductor structure of the p^{++}-AlGaAs:C/n^{++}-GaInP:Te TJ and (right) photograph of the processed diodes.

The key feature of tunnel junctions for their application in MJSC is that, as long as quantum tunneling is the dominant conduction mechanism, they exhibit a linear I–V dependence until the peak tunneling current (J_p) is reached. This initial ohmic region in the I–V curve is ideal for implementing low-loss interconnections between the subcells with different energy bandgaps that constitute a MJSC.

According to this brief introduction, two important requirements can be deduced for TJs.

- They should provide minimum electrical losses in the interconnection (i.e. low voltage drop) by exhibiting low equivalent resistance and high peak tunneling currents. This requirement is specially demanding in ultra-high concentrator applications where photo-generated currents are quite high (~10A/cm^2 for 1000 suns up to ~150A/cm^2 for 15000 suns).
- They should be transparent (i.e. non-absorbing) for the light passing to underlying subcells.

In terms of materials to implement the TJ, these two requirements point to opposite directions. High transparency is obtained by choosing high-bandgap materials while the highest peak tunneling currents are obtained by using low-bandgap materials, which suffer from higher light absorption. Hence, optimization of the bandgap materials used in order to get a trade-off between high peak tunneling current and high optical transmission is required when working at high concentrations.

In previous work by the III-V semiconductor group at IES-UPM (Solar Energy Institute of the Technical University of Madrid), a p^{++}-AlGaAs:C/n^{++}-GaAs:Te design was presented with the highest J_p reported to date (10,000A/cm^2) for a TJ in the field of MJSCs. With the aim of improving the transparency of this TJ, a new design was implemented by substituting the GaAs cathode by a heavily Te-doped GaInP layer, in the quest for a p^{++}-AlGaAs:C/n^{++}-GaInP:Te design. The goal of this TJ is to work as a connection between the GaInP top cell and the Ga(In)As middle cell in a lattice-matched GaInP/Ga(In)As/Ge triple-junction solar cell.

For electrical characterization of the TJ, a test structure was grown on a (100) GaAs wafer, mis-oriented 2º towards the nearest (111) A plane, by metal-organic vapor phase epitaxy (MOVPE). The heavily doped p–n junction was grown after 20nm of GaInP:Si, which is the material used for the window layer of the middle cell in a real MJSC structure (see Figure 1 left). After these layers, a GaAs cap layer was grown to facilitate the formation of ohmic contacts.

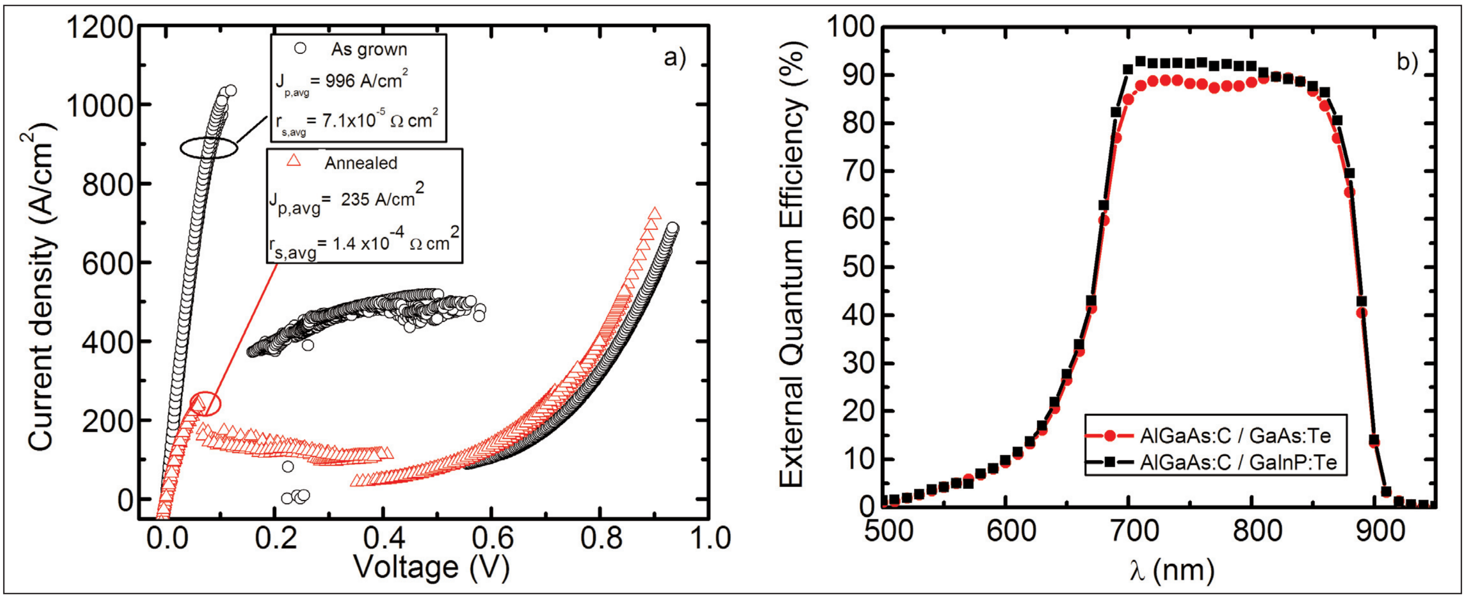

Figure 2 (a) J–V measurements of p^{++}-AlGaAs:C/n^{++}-GaInP:Te TJs fabricated with the as-grown structures (black circles) and after thermal annealing at 675ºC for 30 min (red triangles) and (b) EQE measurements of GaInAs SCs with a p^{++}-AlGaAs:C/n^{++}-GaInP:Te (black squares) and a p^{++}-AlGaAs:C/n^{++}-GaAs:Te (red circles) TJ on top. The results are plotted for devices with ARC.

It has been widely reported in the literature that TJs suffer from thermal degradation. So, when grown as individual test devices, they typically show much better characteristics than when grown in real structures where the thermal load is higher. To take this effect into account and simulate the thermal load that the TJ will suffer during growth of the rest of the layers of a complete MJSC structure, a second identical sample was grown and subsequently annealed at 675º for 30 minutes to simulate the thermal load associated with growth of the MJSC's top cell. The front contact metallization of both samples was formed with AuZn, and AuGe/Ni/Au was used for the back contact (see Figure 1 right).

The J–V curves were measured for both samples with the 4-point probe technique. As can be seen from Figure 2(a), an average J_p of 996A/cm^2 was obtained, together with a specific resistance of 7x10^{-5}Ωcm^2, for as-grown samples. The sample that suffered additional thermal load showed a reduced peak tunneling current of 235A/cm^2, which is also high enough to allow the TJ to operate in the ohmic region up to ultra-high concentrations of 15,000 suns. In this second case, the specific resistance increased to 1.4 x10^{-4}Ωcm^2, which is still a value low enough to guarantee a negligible voltage drop, even at ultra-high concentrations.

In relation to the optical properties of this new TJ structure, the external quantum efficiency (EQE) was measured to verify the current gain in the middle subcell because of a lower optical absorption. For that, two new samples were performed by using Ge (100) substrates. Two samples were grown. For one, after growth of the middle cell, a lower-bandgap TJ was grown (p^{++}-AlGaAs/n^{++}-GaAs). The other one had a new high-bandgap design (p^{++}-AlGaAs:C/n^{++}-GaInP:Te). In both structures, after the TJ growth, a GaInP layer of 750nm was grown, mimicking the top-cell absorption.

The same anti-reflection coating layer was deposited on both samples prior to EQE measurement. As can be seen (Figure 2(b)), the EQE of the samples with a high-bandgap tunnel junction is improved due to the higher transparency of this design, allowing more light to reach the middle subcell. This EQE improvement results in a current gain around 0.56A/cm^2 when considering the AM 1.5 D ASTMG 173-03 (1000W/m^2) spectrum.

All these characteristics indicate that this TJ structure can be integrated in a MJSC without being the limiting component of the device when working at even ultra-high concentrations (15,000 suns). All the work (simulation of structures, epitaxial growth by MOVPE and electrical and optical measurements) was carried out at IES-UPM.

These structures are being implemented in an optimized triple-junction solar cell that is intended to exceed efficiencies of 40% working at ultra-high concentrations. ■

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